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14. ABSTRACT Cancer stem cells (CSCs), a cell population with acquired perpetuating self-renewal properties which resemble normal stem cells, specifically in the ability to infinitely give rise to the bulk of a tumor as the "seed" of the cancer, account for cancer initiation, progression, recurrence, and chemo-resistance. The cell polarity machinery has been strongly suspected of playing an evolutionarily-conserved role in regulating the cell fate in both normal and neoplastic stem cell populations, which suggests that therapeutic targeting of this mechanism may be an effective strategy for eliminating CSCs and thereby impeding cancer progression and recurrence. During the first grant period, we have successfully completed the proposed studies in Aim1 and have also made significant progress in the ongoing experiments in Aim2. Our results collectively support the hypothesis that PKCzeta is a novel target of microRNA-200c (miR-200c), the most significantly down-regulated miRNA in breast CSCs. Dysregulation of miR200c-PKCzeta signaling is critical for sustaining a self-renewing breast CSC pool and is associated with high-grade aggressive breast cancer. Together, these data point to a great potential for the strategies targeting PKCzeta signaling to exhaust the CSC pool for treatment of breast cancer.					
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## 1. Introduction

Cancer stem cells (CSCs), a cell population with acquired perpetuating self-renewal properties which resemble normal stem cells, specifically in the ability to infinitely give rise to the bulk of a tumor as the “seed” of the cancer, account for cancer initiation, progression, recurrence, and chemo-resistance. To date, treatment strategies designed to eliminate CSCs still remain a significant challenge, and delineation of the underlying mechanism(s) governing the cell fate decision to maintain self-renewal properties in CSCs likely holds the key to the development of effective treatments that can eradicate the genesis of cancer. The cell polarity machinery has been strongly implied to play an evolutionarily-conserved role in regulating cell fate in both normal stem cells and cancer stem cells (CSCs), suggesting that therapeutic targeting of this mechanism may be an effective strategy that can be applied to eliminate CSCs and thereby to impede cancer progression, recurrence, and chemo-resistance. However, the precise critical cell polarity components and mechanisms involved in the regulation of CSC cell fate still remain to be defined. Notably, asymmetric divisions (AD) is a critical mechanism which ensures self-renewal during proliferation of mammalian stem cells, where a family of cell polarity proteins, atypical Protein Kinase C (aPKC), phosphorylates the cell fate determinant NUMB, which in turn directs the polarized distribution of NUMB exclusively to the daughter cell with the differentiated cell fate, allowing the opposite daughter cell that accumulates aPKC to maintain the stem cell identity. In contrast, loss of PKC $\zeta$  expression/activity leads to a uniform distribution of NUMB with the consequent symmetric commitment (SC) of both daughter cells to the differentiated cell fate, resulting in exhaustion of the stem cell pool. Interestingly, our preliminary data provide the first evidence showing that a member of the aPKC family, PKC $\zeta$ , is a novel target of microRNA-200c (miR-200c), a microRNA known to be significantly down-regulated in breast CSCs. Our own previous findings and the preliminary results in this study further elucidate that loss of miR-200c not only leads to the gain of stem cell properties to generate a CSC-like population, but also enhances AD to sustain the CSC pool, potentially through upregulation of PKC $\zeta$ . Even though these findings provide evidence to support a role of miR200c-PKC $\zeta$  axis in regulation of breast CSCs, the precise underlying mechanism that links the regulation of PKC $\zeta$  to the breast CSC fate remain to be delineated, and the analysis system to elucidate the dynamic changes of the CSC fate decision (AD vs. SC) has yet to be established. As a consequence, there remains a critical need to determine the mechanisms by which the CSC fate is regulated, since, in the absence of such knowledge, the development of effective therapeutic interventions to target CSCs and prevent cancer progression and recurrence will likely remain limited. Based on supporting evidence and our own preliminary data, our central hypothesis is that upregulation of PKC $\zeta$  expression is critical for promoting AD to sustain a self-renewing CSC pool, and that strategies targeting PKC $\zeta$  signaling will be therapeutically effective in treating breast cancer by exhausting CSCs. To test the hypothesis, we propose the following aims: Aim 1 will determine the key cell polarity mechanism(s) involved in regulation of breast CSCs, and Aim 2 will develop a therapeutic strategy targeting the cell polarity machinery to direct breast CSC fate. At the completion of this project, it is our expectation that we will have revealed a novel role of miR-200c- PKC $\zeta$  signaling in regulation of the polarity of breast CSC division and the consequent cell fate, and have provided new and important clinical implication of PKC $\zeta$  inhibitor in breast cancer treatment. Under the support of this award, we have made the following progress during the **second** grant period (Sep 30, 2016- Oct 1, 2017).

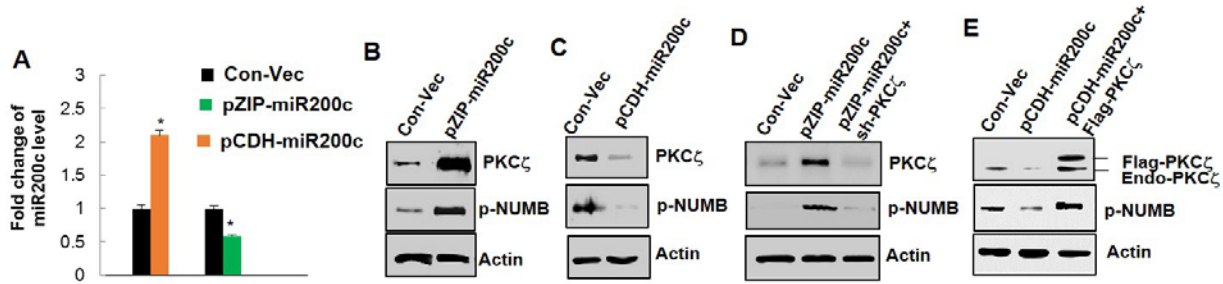
## **2. Keywords**

Breast cancer, PKCzeta, MicroRNA, Cancer stem cell, Cell fate determinant, Cell polarity

### 3. Accomplishments

- Goals and Accomplishments:

**Specific Aim 1: Determine the key cell polarity mechanism(s) involved in regulation of breast CSCs**



**Figure 1. PKC $\zeta$  is a bona fide miR-200c target.** (A) MiR-200c expression levels (n=3 independent experiments, asterisk indicates P<0.05, error bars denote  $\pm$ SD), and (B-C) PKC $\zeta$  and p-NUMB protein levels in MCF7-pZIP-miR200c cells that stably expressed sh-miR200c, in BT549-pCDH-miR200c cells that stably expressed miR-200c, and in the control cells expressing the control vectors. (D-E) PKC $\zeta$  and p-NUMB protein levels in MCF7-pZIP-miR200c cells that further expressed sh-PKC $\zeta$ , in BT549-pCDH-miR200c cells that further expressed PKC $\zeta$  cDNA, and in the control cells expressing the control vectors.

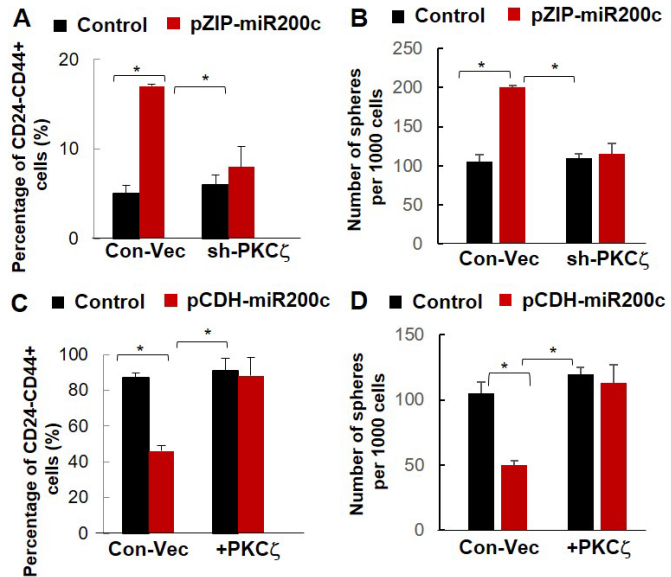
Major Task 1: Determine the role of miR200c-PKC $\zeta$  signaling in regulation of breast CSCs (Months 1-8)

Subtask 1: Establish BT549 cells that stably express miR-200c (pCDH-miR200c) and MCF7 cells with knock-down of miR-200c (pZIP-miR200c) (Months 1-2) **Completed!**

We have successfully established BT549-pCDH-miR200c and MCF7-pZIP-miR200c and examined the protein expression levels as described in subtask 2 (Fig. 1).

Subtask 2: Determine expression levels of PKC $\zeta$  and phospho-NUMB (p-NUMB), by re-expressing PKC $\zeta$  in BT549-pCDH-miR200c cells and knocking-down PKC $\zeta$  in MCF7-pZIP-miR200c cells (Months 3-5) **Completed!**

We have successfully demonstrated that PKC $\zeta$  is a bona fide miR-200c target. PKC $\zeta$  protein expression and the phosphorylation level of its substrate p-NUMB are markedly



**Figure 2. MiR-200c suppresses breast CSC traits through down-regulation of PKC $\zeta$ .** (A) The percentage of isolated CD24-CD44 $^{+}$  population, and (B) the number of tumor spheres (sphere size>100 $\mu$ m) per 1000 initially plated cells from MCF7-pZIP-miR200c cells that further expressed sh-PKC $\zeta$ . (C) The percentage of isolated CD24-CD44 $^{+}$  population and (D) the number of tumor spheres (sphere size>100 $\mu$ m) per 1000 initially plated cells from BT549-pCDH-miR200c cells that further expressed PKC $\zeta$ . n=3 independent experiments, asterisk indicates P<0.05. Error bars denote  $\pm$ SD.

upregulated by knock-down of miR-200c in MCF7-pZIP-miR200c cells, which can be reversed by knock-down of PKC $\zeta$ . Consistently, PKC $\zeta$  protein expression and the phosphorylation level of its substrate p-NUMB are downregulated by ectopic expression of miR-200c in BT549-pCDH-miR200c cells, which can be rescued by re-expression of PKC $\zeta$  (Fig. 1).

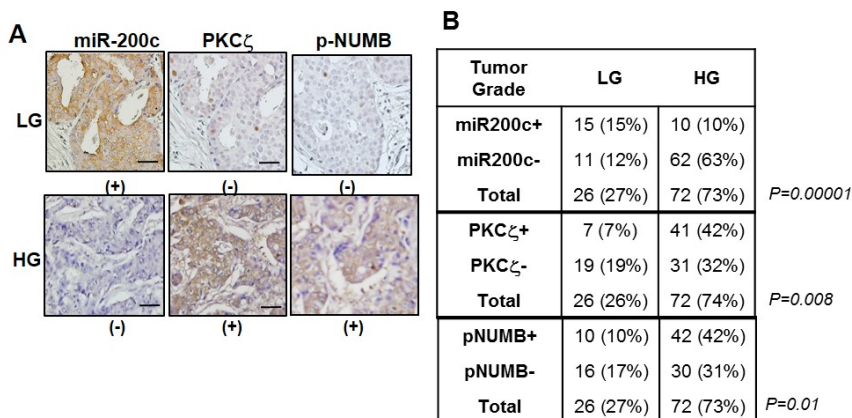
Subtask 3: Determine changes in the percentage of CD24-CD44<sup>+</sup> cells and the sphere forming capacity by ectopically expressing PKC $\zeta$  in BT549-pCDH-miR200c cells and knocking-down PKC $\zeta$  in MCF7-pZIP-miR200c cells (Months 6-8) **Completed!**

We have successfully demonstrated that the percentage of CD24<sup>+</sup>CD44<sup>+</sup> cells and the sphere forming capacity are markedly enhanced by knock-down of miR-200c in MCF7-pZIP-miR200c cells, which can be reversed by knock-down of PKC $\zeta$ . Consistently, the percentage of CD24<sup>+</sup>CD44<sup>+</sup> cells and the sphere forming capacity are suppressed by ectopic expression of miR-200c in BT549-pCDH-miR200c cells, which can be rescued by re-expression of PKC $\zeta$  (Fig. 2).

Major Task 2: Determine the correlation of miR200c-PKC $\zeta$  regulation with clinicopathological characteristics in human breast tissue samples (Months 9-14)

Subtask 1: Determine the expression levels of miR-200c, PKC $\zeta$ , p-NUMB by in situ hybridization or immunohistochemical staining in 150 human breast tumor samples (consecutive FFPE tissue sections) collected from the Susan G. Komen for the Cure® Tissue Bank at Indiana University (Months 9-12) **Completed!**

We have performed a correlation analysis of PKC $\zeta$ , p-NUMB, and miR-200c expression levels in human breast tissue specimens consisting of a cohort of breast tumor samples. We have successfully demonstrated that PKC $\zeta$  and p-NUMB levels are repressed in the well-differentiated low tumor grade breast tumors (LG, grade I), where miR-200c was highly expressed (Fig. 3, n=98). In contrast, the poorly-differentiated high tumor grade tumors (HG, grade II-III) exhibit overexpression of PKC $\zeta$  and p-NUMB, along with significantly reduced miR-200c levels (Fig. 3, n=98).



**Figure 3. Lost miR200c expression is correlated with overexpression of PKC $\zeta$  and p-NUMB in high-grade, aggressive breast cancer. (A)** Representative IHC staining images showing expression levels of miR-200c, PKC $\zeta$  and p-NUMB in 98 human breast tissue specimens, including low-grade tumors (tumor grade I, LG) and high-grade tumors (tumor grade II-III, HG, scale bar: 100 $\mu$ m). **(B)** Correlation of miR-200c, PKC $\zeta$  and p-NUMB expression levels with tumor grade was analyzed by Chi-Square analysis. (-): negative-low staining, (+): strong-positive staining.



Subtask 2: Correlation analysis of the protein levels among miR-200c, PKC $\zeta$ , p-NUMB and their correlation with tumor subtype (p53, BRCA1, ER/PR/HER2 status), tumor grade (differentiation status), tumor stage (metastasis status), and 5 year recurrence status (Months 13-14) **Ongoing**

**We are continuously working with Dr. Weng on correlation analysis of miR-200c, PKC $\zeta$ , p-NUMB expression with tumor subtype (p53, BRCA1, ER/PR/HER2 status), tumor stage (metastasis status), and 5 year recurrence status.**

**Specific Aim 2: Develop a therapeutic strategy targeting the cell polarity machinery to direct breast CSC fate**

**Major Task 3:**

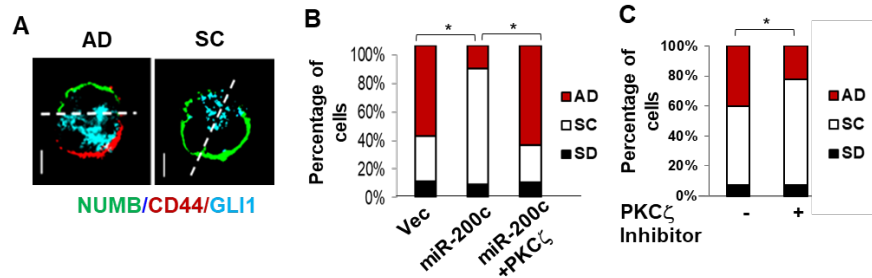
**Determine the role of miR200c-PKC $\zeta$  signaling in regulation of the polarity of breast CSC division (Months 15-20)**

Subtask 1: Confocal fluorescence paired cell imaging of GLI1-CFP, CD44, and NUMB will be analyzed during the first division of the breast CSCs expressing the control vector, miR-200c, and miR-200c+PKC $\zeta$  expression plasmids or under the treatment of vehicle/PKC $\zeta$  inhibitor (Months 15-17) **Completed!**

**We have established and analyzed the paired cell image patterns (AD vs. SC) using GLI1-CFP, CD44, and NUMB in the breast CSCs expressing miR-200c, and miR-200c+PKC $\zeta$  expression plasmids or under the treatment of vehicle/PKC $\zeta$  inhibitor. We have successfully demonstrated that inhibition of PKC $\zeta$  by PKC $\zeta$  inhibitor treatment leads to a markedly increased symmetric commitment (SC) along with a reduced asymmetric division (AD, Fig. 4); similar effects can be recapitulated by enforced expression of miR-200c, which are then reversed upon re-expression of PKC $\zeta$  (Fig. 4).**

Subtask 2: Serial sphere formation assay with repeated dissociation of spheres into single cells followed by re-formation of spheres for three consecutive passages using breast CSCs expressing the control vector, miR-200c, and miR-200c+PKC $\zeta$  expression plasmids or under the treatment of vehicle/PKC $\zeta$  inhibitor (Months 18-20) **Completed!**

**We have established the sphere cultures expressing control vector, miR-200c, and miR-200c+PKC $\zeta$  plasmids. The number of spheres per 1000 plated cells has been analyzed from three independent experiments of three serial passages. We have successfully demonstrated that inhibition of PKC $\zeta$  by PKC $\zeta$  inhibitor treatment leads to continuing**



**Figure 4. Inhibition of PKC $\zeta$  leads to symmetric commitment of breast CSCs to favor the differentiation cell fate. (A)** Representative images showing intracellular distribution of CD44 (red), NUMB (green), and GLI1-CFP reporter (aquamarine) in the dividing CSCs during asymmetric cell division (AD) or symmetric lineage commitment (SC) of the CD24-CD44<sup>high</sup>-CSC population isolated from BT549 cells (scale bar: 10 $\mu$ m). **(B)** The percentage the CSCs that manifested specific division pattern from BT549 cells expressing miR-200c, miR-200c+PKC $\zeta$ , or control vector, and from **(C)** the primary breast CSCs treated with PKC $\zeta$  inhibitor or vehicle. n=3 independent experiments, asterisk indicates P<0.05. Error bars denote  $\pm$ SD.



diminishment of the spheres at each passage; similar effects can be recapitulated by enforced expression of miR-200c, which are then reversed upon re-expression of PKC $\zeta$  (Fig. 5).

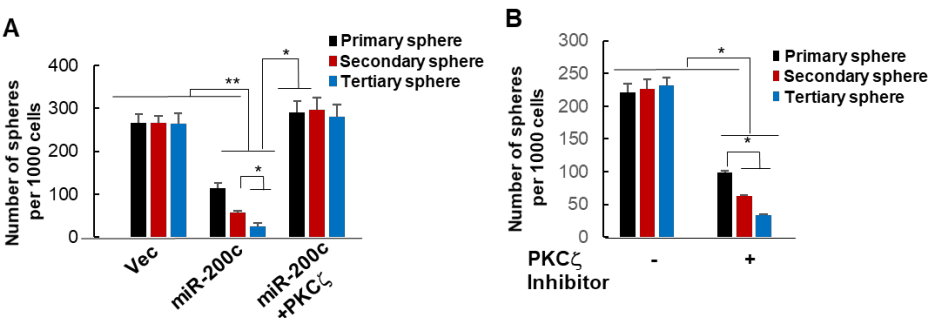
Major Task 4:  
Determine the  
therapeutic effect  
of targeting  
miR200c-PKC $\zeta$   
signaling in vivo

Subtask 1:

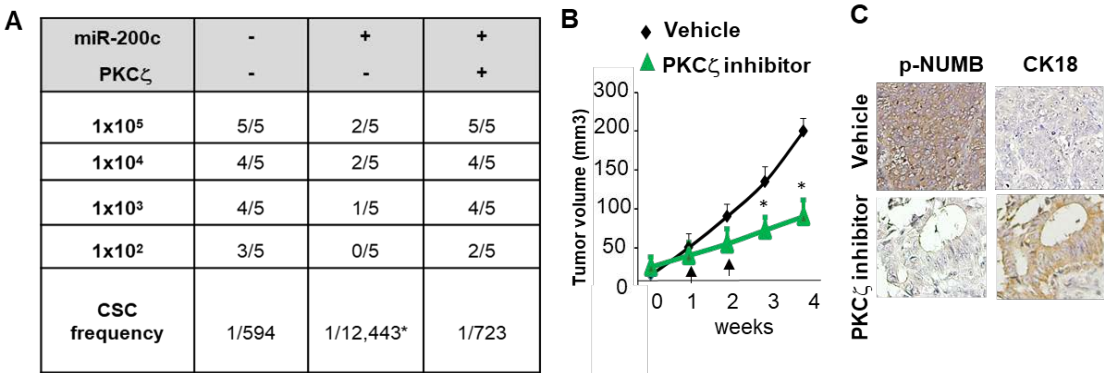
Determine the  
expected  
tumorigenic CSC  
frequency of  
primary breast  
CSCs stably

expressing miR-200c, miR-200c+ PKC $\zeta$ , and the control plasmids in mammary tumor  
xenograft animals using Extreme Limiting Dilution Analysis (Months 21-24) **Completed!**

We have successfully demonstrated that down-regulation of PKC $\zeta$  by miR-200c  
significantly inhibits mammary xenograft tumor formation with a significant reduction in  
the tumor-seeding CSC frequency, and these effects are reversed upon re-expression of  
PKC $\zeta$  (Fig. 6A).



**Figure 5. Inhibition of PKC $\zeta$  leads to exhaustion of breast CSCs.** (A) The number of the serially passaged tumor spheres from BT549-CSCs expressing miR-200c, miR-200c+PKC $\zeta$ , or control vector, and from (B) the primary breast CSCs treated with PKC $\zeta$  inhibitor or vehicle. n=3 independent experiments, asterisk indicates P<0.05; double asterisk indicates P<0.01. Error bars denote  $\pm$ SD.



**Fig. 6. Inhibition of PKC $\zeta$  effectively suppresses tumorigenic CSCs and xenograft tumor growth.** (A) The calculated CSC frequency by the xenograft tumor formation in NOD/SCID mice inoculated with the indicated number of primary human breast tumor cells that stably expressed miR-200c, miR-200c+PKC $\zeta$ , or control vector using Extreme Limiting Dilution Analysis. (B) Tumor xenograft growth, and (C) p-NUMB and CK18 staining in tumor sections from NOD/SCID mice under PKC $\zeta$  inhibitor (ip, 20 mg/kg, every other day) or vehicle treatment for two weeks (n=6 animals/group, asterisk indicates P<0.05). Error bars denote  $\pm$ SD.

Subtask 2: Determine the therapeutic effect of PKC $\zeta$  inhibitor on overcoming doxorubicin-resistance in NOD/SCID mice inoculated with primary breast CSCs stably expressing the

GLI1-activity reporter (Months 25-28) **Ongoing**

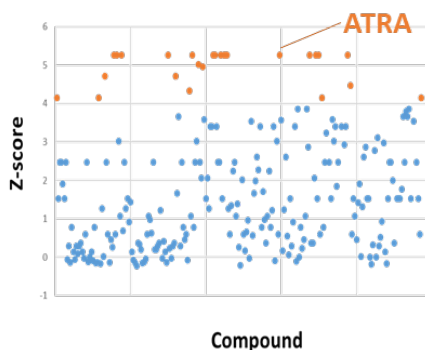
**We have successfully demonstrated the therapeutic efficacy of PKC inhibitor in suppression of breast tumor xenograft tumor (PDX) growth as well as its effect on causing the poorly-differentiated high-grade adenocarcinoma phenotype to revert to a well-differentiated tumor phenotype with expression of the luminal lineage marker CK18, pointing to a commitment to the luminal differentiation (Fig. 6B-6C). We are currently working on determining the maximum tolerated dose and toxicity of the combination treatment (PKC $\zeta$  inhibitor-doxorubicin) in tumor bearing NOD/SCID mice.**

Major Task 5: Identify new lead compounds that impact the polarity of breast CSC division using phenotypic screening

Subtask 1: High throughput phenotypic screening (HTS) of compound libraries to identify the ones that direct primary breast CSCs to symmetric commitment (SC, SYC) by high content paired cell imaging analysis (Months 29-31) **Ongoing**

**We have collaborated with Purdue Drug Discovery Core Facility to perform the paired cell analysis based-HTS screening. Hit compounds determined as > 2-fold increase in SYC division pattern and Z score > 5 were selected (Fig. 7). All-trans retinoic acid (ATRA) was identified as one of the hits, and its role in directing CSC to SYC fate has been validated in our recent publication (Wu et al., Oncogene, 2017)**

Subtask 2: Determine the dose response curve by exposing the primary breast CSCs to the candidate SC-promoting compounds identified from subtask1 at twelve different concentrations with two-fold serial dilutions between 0 and 100 $\mu$ M in triplicate using non-linear regression analysis (Prism software) (Months 32-33) **Not started**



**Figure 7.**  
**Selection of**  
**SYC promoting**  
**drugs from**  
**paired cell**  
**imaging- based**  
**high throughput**  
**screening (HTS)**

Subtask 3: Serial sphere formation assay with repeated dissociation of spheres into single cells followed by re-formation of spheres for three consecutive passages using the primary breast CSCs under the treatment of the hit compounds identified from subtask1 with the effective concentrations (EC50) confirmed in subtask 2. (Months 34-36) **Not started**

- **Opportunities for training and professional development:**

1. The award provides professional development for the PI, Chun-Ju Chang, for making tenure and promotion to Associate Professor in May 2017.
2. The award provides training opportunities to the postdoc fellow, Yu-Syuan Chen, and the graduate student, Meng-Ju Wu, to receive courses, mentoring, and research experience that have advanced their professional skills.

3. The award provides professional development opportunities to the graduate student, Meng-Ju Wu, for participation in conferences, such as 2017 American Association of Cancer Research Annual Conference.

- **Results disseminated to communities of interest:**

Nothing to report

- **Plan to do during the next reporting period to accomplish the goals:**

We have successfully completed the proposed studies in Aim1 and Aim2 with the results that are highly supportive of our central hypothesis. We will continue determining the therapeutic effect of a specific PKC $\zeta$  inhibitor in the breast cancer xenograft animals and validate the SC-promoting compounds in regulation of CSC capacity as planned in the major task 4 and 5 during the next reporting period.

## **4. Impact**

### **The impact on the development of the principal discipline(s) of the project:**

About 1 in 8 U.S. women will develop breast cancer over the course of her lifetime, and in the year of 2017, breast cancer has claimed the lives of more than 40,000 women and men in the United States. Although initial remission can be achieved with chemo-treatments, the worry and fear of treatment resistance, recurrence, and death still have a deep impact on many breast cancer patients. It is recognized that cancer stem cells (CSCs), a long-lived, self-perpetuating cell population that can infinitely give rise to the bulk of a tumor as the “seed” of the cancer, account for cancer initiation, progression, radio-/chemo-resistance, and recurrence. To date, treatment strategies designed to eliminate the genesis of the cancer (CSC) still remain a significant challenge. This project aims to identify critical cell components and their working mechanisms that are used to sustain the breast CSC pool, and the identified mechanism will further be therapeutically targeted to direct CSCs to a terminally dormant cell fate and become sensitive towards radio-/chemo-therapy. With the common properties of CSCs between many cancer types, we believe that the applications generated from our research will continually contribute to overcoming the therapeutic hurdles of a broad spectrum of cancers and significantly benefit the cancer patient and the survivor community for decades.

### **The impact on other disciplines:**

Nothing to report.

### **The impact on technology transfer:**

Nothing to report.

### **The impact on society beyond science and technology:**

Nothing to report.

## **5. Changes/Problems**

Nothing to report

## 6. Products

- **Publications, conference papers, and presentations:**

(1) Journal publications (#: corresponding author):

- a. Wu MJ, Chen YS, and Chang C-J<sup>#</sup> (2017) Retinoic acid directs stem cell fate through regulation of TET2-PKC $\zeta$  pathway in breast cancer. *Oncogene* 1;36(22):3193-3206 (Published, acknowledgement of federal support-yes)
- b. Wu MJ, Kim M, and Chang C-J<sup>#</sup> (2017). EMT directs the polarity of mammary stem cell fate. *Nature communication* (Submitted, acknowledgement of federal support-yes)

(2) Presentations:

- a. 2016 Keystone Symposia- Stem Cells & Cancer, Breckenridge, “Epigenetic regulation promotes obesity related breast cancer progression”
- b. 2016 Annual Meeting of International Society for Stem Cell Research, San Francisco, CA “The role of miR200c in ATRA-mediated differentiation of breast cancer stem cells”
- c. 2017 American Association of Cancer Research Annual Conference. “Retinoic acid directs breast stem cell fate through regulation of TET2-PKC $\zeta$  pathway”
- d. 2016 & 2017 Purdue University Center for Cancer Research Annual Retreat, West Lafayette, IN “The role of Tet2 in mammary stem cell fate and tumorigenesis”

- **Technologies, inventions, patent applications, and/or licenses:**

Nothing to report.

- **Other Products:**

- a. Establishment and validation of BT549-pCDH-miR200c cells that stably express miR-200c and MCF7-pZIP-miR200c cells that stably knock-down miR-200c. These cell lines will be used for proposed in vivo experiments.
- b. Generation of ChIP-sequencing and microarray datasets (GSE85189,

GSE85141) as reported in the newly-accepted Oncogene paper (6-1-a).

c. Patent application: paired cell imaging analysis-based high throughput drug screening (In preparation for submission)



## **7. Participants & Other Collaborating Organizations**

- **Individuals and other support:**  
Nothing to report.
- **Other involved organizations:**  
Nothing to report.

## **8. Special Reporting Requirements**

Nothing to report.

## 9. Appendices

The abstract of our published manuscript “Retinoic acid directs breast cancer cell state changes through regulation of TET2-PKC $\zeta$  pathway in breast cancer” in *Oncogene*. 2017 Jun 1;36(22):3193-3206. doi: 10.1038/onc.2016.467

### Abstract:

The key molecular mechanism governing the stem cell fate to control the cancer stem cell (CSC) pool remains elusive. This study provides the first evidence showing that all-trans retinoic acid (ATRA) induces the interaction and chromatin recruitment of a novel RAR $\beta$ -TET2 complex to epigenetically activate a specific cohort of gene targets, including *MiR-200c*. TET2-activated miR-200c further targets and suppresses PKC $\zeta$ , a cell polarity protein that plays a pivotal role in directing self-renewing asymmetric division of mammalian stem cells to sustain the stem cell pool. Our data reveals that pharmacological concentration of ATRA effectively downregulates PKC $\zeta$  through activation of miR-200c, leading to exhaustion of the stem cell-like populations from non-tumorigenic mammary epithelial cells and non-aggressive breast cancer cells. However, aggressive breast cancer cells that manifest TET2-miR200c dysregulation sustain a self-renewing CSC pool highly resistant to ATRA, where inhibition of PKC $\zeta$  significantly suppresses of the resistant CSCs. Together, these findings elucidate a novel TET2-miR200c-PKC $\zeta$  signaling pathway that governs the stem cell fate to eradicate breast cancer.